Formation, Detection, and Characterization of Extrasolar Habitable Planets
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The ELODIE and SOPHIE Search for Northern Extrasolar Planets: Jupiter-Analogs around Sun-Like Stars†

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Abstract. We present radial-velocity measurements (RV) obtained in one of the numbers of programs underway to search for extrasolar planets with the spectrograph SOPHIE at the 1.93-m telescope of the Observatoire de Haute-Provence. Targets were selected from catalogs observed with ELODIE, which had been mounted previously at the telescope, in order to detect long-period planets with an extended database close to 15 years.

Keywords. planetary systems – techniques: radial velocimetry – magnetic cycle

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1. New long-period giant planets and refined orbits

RV tables are available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/

2. Are we observing magnetic cycle ?

The amplitudes of the RV variations are greater in the case of all stars than for all the reported active cycles in the literature (Baliunas *et al.* 1995, Lovis *et al.* 2011). We did not find any long-term correlations between the RV and the activity index in the SOPHIE measurements. We concluded that the most likely explanation of the observed RV variations is the presence of a planet.

3. A new population of long-period Jupiter-mass planets

We increase to 19 the number of planets further than 4 AU characterized from RV measurements. With planets published with partial observations (i.e. where the orbital period was not completely covered) and a small number of objects, it has been difficult to

† Based on observations made with the ELODIE and the SOPHIE spectrographs on the 1.93-m telescope at Observatoire de Haute-Provence (OHP, CNRS/OAMP), France (program 07A.PNP.CONS) and on spectral data retrieved from the ELODIE archive at OHP.

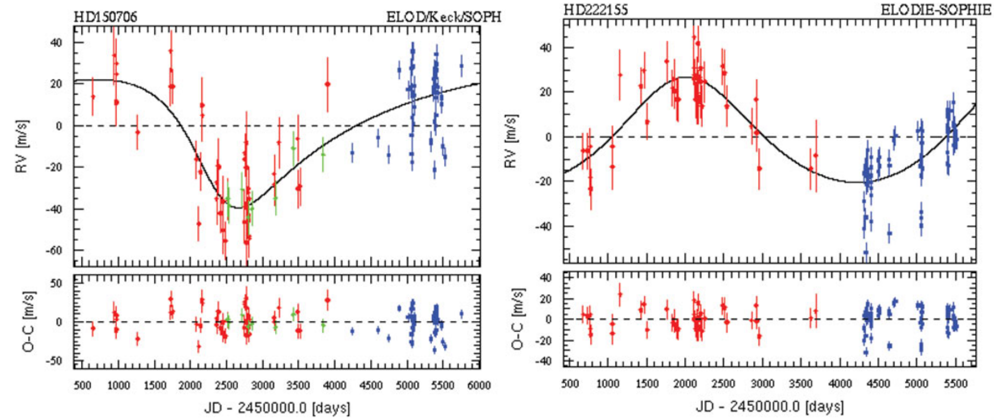

Figure 1. Left: ELODIE (red), Keck (green), and SOPHIE (blue) RV data points and their residuals from the best-fit Keplerian model for HD150706 as a function of barycentric Julian date. The best-fit Keplerian model is represented by the black curve with a reduced χ^2 equal to 2.6. The period is 16.1 yr with a slight eccentricity $e = 0.38^{+0.28}_{-0.32}$ and the planet minimum mass is 2.71 M_{Jup}. **Right:** ELODIE (red) and SOPHIE (blue) RV and residuals from the best-fit Keplerian model for HD222155 as a function of barycentric Julian date. The best-fit Keplerian model is represented by the black curve with a reduced χ^2 equal to 2.2. The planet has a period of 10.9 yr in a non-significant eccentric orbit ($e = 0.16^{+0.27}_{-0.22}$), and a minimum mass of 1.90 M_{Jup}.

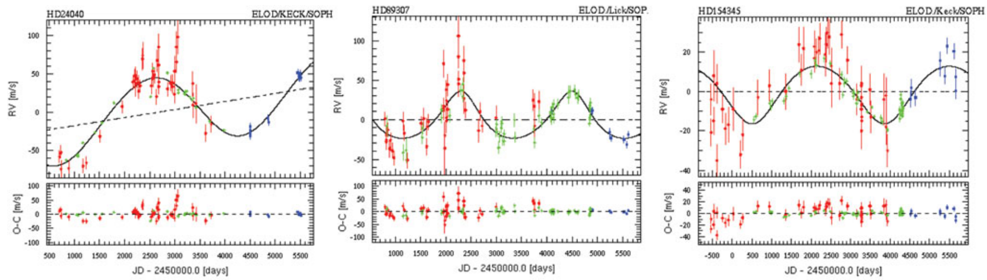

Figure 2. Left: ELODIE (red), Keck (green) SOPHIE (blue) RV and residuals to the best-fit Keplerian model (black curve) for HD24040 as a function of barycentric Julian date. It shows a 4.01 M_{Jup} companion with an orbital period of 10.0 yr. A linear trend is fitted simultaneously pointing out the presence of a third body in the system. A massive companion was announced previously by Wright *et al.* (2007). **Middle:** ELODIE (blue), Lick (green), and SOPHIE (red) RV and residuals from the best-fit Keplerian model (black curve) for HD89307 as a function of time. The fitted orbit corresponds to a planet with a minimum mass of 2.0 M_{Jup}, a period of 6.0 yr, and a slightly eccentricity orbit $e = 0.25 \pm 0.09$ in agreement with Fischer *et al.* (2009). **Right:** ELODIE (red), Keck (green), and SOPHIE (blue) RV and residuals of the best-fit Keplerian model (black curve) for HD154345 as a function of barycentric Julian date. The companion has a period of 9.7 yr, and a minimum mass of 1.0 M_{Jup} agreeing with Wright *et al.* (2008).

establish any significant statistical trends. Nevertheless, we discuss the main properties of this new population.

These planets are in multiplanetary systems (10 of 19 candidates). Their eccentricity distribution agrees with current observations of a significant dispersion. Most of the host stars are G-type stars (observational bias) and are significantly more metal-rich than average.

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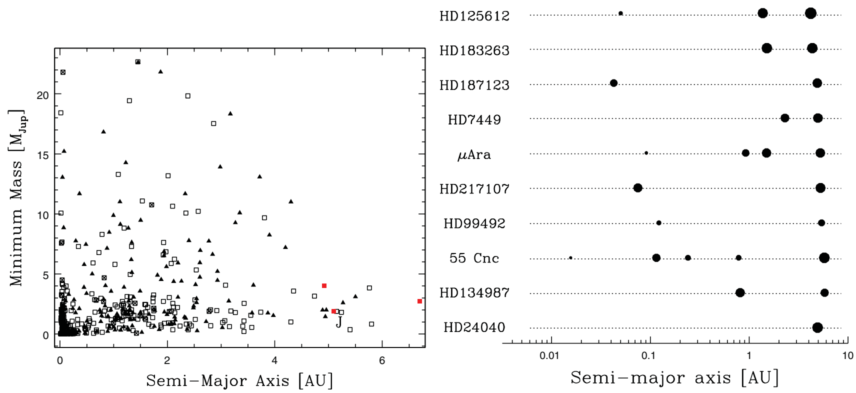

Figure 3. Left: Minimum mass as a function of the semi-major axis for all planets detected by RV and transit surveys. Empty squared symbols (filled triangles) represent planets with eccentricities lower (higher) than 0.25. Crosses indicate fixed eccentricities at $e = 0$. Jupiter is on the plot. Red points are the Jupiter-like planets characterized in this paper: HD150706b, HD222155b, and HD24040b. **Right:** Multiple systems with semi-major axis greater than 4 AU. The size of the dots shows the minimum mass of the planet on a log scale.

A lack of massive planets at long period ? A solid prediction of the core-accretion formation theory

We remark that no very massive planet (>8 M_{Jup}) was found. Such a distribution agrees with population synthesis (Mordasini *et al.* 2012), where they showed that a decrease in frequency of massive giants planets at large distance (>4-5 AU) is a solid prediction of the core-accretion theory.

The occurrence rate of planets with minimum masses higher than 8 M_{Jup} is 1/19 for semi-major axes a > 4 AU compared to 27/196 (∼1/7) for smaller orbits with $1 < a < 4$ AU. Assuming a binomial distribution, this implies that 13.8±2.5% of the planets with semi-major axes in the range $1 < a < 4$ AU and 5.3±22.3% for those with semi-major axes a>4 AU have minimum masses higher than 8 M_{Jup}. It is unlikely that these host stars would have been discarded from planet surveys as single-lined spectroscopic binaries: for instance, a 8 M_{Jup} orbiting in 4000 days a one solar-mass star induces a RV semi-amplitude of 102m/s for a circular orbit, which leads to a typical linear slope of ∼37m/s/yr.

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